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ScienceDirect
Energy Procedia 91 (2016) 537 – 545
Energy Procedia

SHC 2015, International Conference on Solar Heating and Cooling for Buildings and Industry

Solar district heating systems for small districts with medium scale seasonal thermal energy stores

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Abstract

This contribution deals with recently realized as well as planned small solar district heating systems with seasonal thermal energy stores in Europe. It focuses on systems with less than 1 000 m^2 of solar collector area and less than 1 000 m^3 volume of seasonal thermal energy store. Different technical characteristics of systems in Poland, Spain and Germany are shown. As high storage efficiency in small systems is difficult to achieve, particular attention is given to the design of the seasonal thermal energy stores and other components such as high temperature heat pumps that are necessary to reach an efficient operation of the plant.

Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG

Keywords: Solar district heating; seasonal thermal energy storage; small scale dirstrict heating systems

1. Introduction

During recent years, solar district heating systems with seasonal thermal energy stores (STES) did not only get larger like the well known Danish projects, efforts have also been made in European and German projects to decrease system size in order to lower investment costs, increase the number of possible applications and realized systems and finally increase the market penetration. The European Union (EU) project EINSTEIN [1] carries out research on the implementation of seasonal thermal energy storage in combination with solar thermal and heat pump technologies. Main focus is on retrofitting applications for the existing building stock. One major part of the project

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Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG
doi:10.1016/j.egypro.2016.06.195

is the demonstration of this technology by demonstration plants. The German research project 1to10 [2] deals with the development and demonstration of a sustainable, standardized solar-geothermal heat supply concept with highly sophisticated thermal energy storage for multi-family houses and small residential areas.

Several small scale solar district heating systems with STES have recently been built and put into operation, e.g. in Warsaw, Poland and Bilbao, Spain. For another system in Crailsheim, Germany the start of construction has begun in October 2015. The systems all have in common that the solar thermal collector area is below 300 m^2. This makes high system efficiency and low heat production cost a challenging task compared to large systems.

While the Spanish system delivers heat for space heating of a cultural event area in a former paper mill and a cafeteria with a total of 1 050 m^2, the Polish system is integrated into a hospital complex. In the first step the administrative building of the hospital is connected to the system to be supplied with solar heat for space heating. The German system is going to deliver heat for space heating and hot water preparation to 43 dwellings in 3 apartment blocks.

2. Spanish system in Bilbao

The system in Bilbao is designed for the heat supply of a former paper mill which is refurbished by the municipality of Bilbao and redesigned for cultural event purposes. It is divided into two main areas – the main event area (800 m^2) and a cafeteria (250 m^2). An under floor heating system and an air heating unit have been installed into the building in order to achieve low heat distribution temperatures of 45 °C on the supply flow respectively 35 °C on the return flow.

2.1. Hydraulic concept

The solar heating system exclusively provides heat for space heating. The solar heat generated by 62 m² of flat plate collectors can either directly be used for heating purposes or is stored in a 183 m³ large over ground hot water store. This store is operated seasonally to store the heat from summer to fall and winter when the heat is required for heating. In order to utilize the stored solar thermal energy more efficiently and to enlarge the usable storage capacity of the STES an electrically driven compression heat pump with a thermal power of 69 kW$_{th}$ using the refrigerant R410a is integrated into the system. As backup heating system a gas boiler with 190 kW is installed. The estimated annual heating demand is 83 MWh/a. The hydraulic schematic of the system is shown in Figure 1.

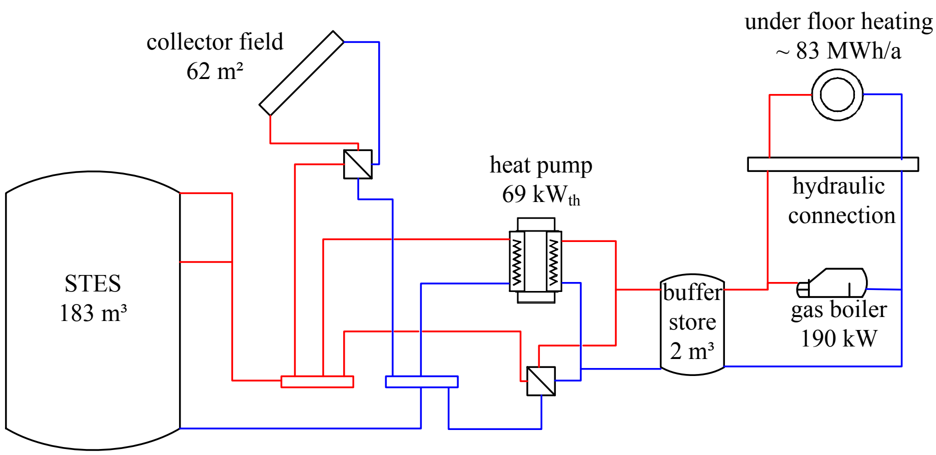

Fig. 1. Simplified hydraulic schematic of the demonstration plant in Bilbao, Spain

3. Polish system in Warsaw

The plant in Warsaw is integrated into a hospital complex. The buildings of the hospital complex are under historical protection. In the first step an administrative building is connected to the system to be supplied with heat for space heating.

3.1. Hydraulic concept

The system consists of a small districted heating network including an over ground hot water store with a volume of 800 m³. In total 151 m² of flat plate collectors are installed. Both the collector field area and the connection to further buildings can be extended in future steps as the STES is already dimensioned accordingly. As the hospital complex buildings are under historical protection, retrofitting measures on the building level are challenging and costly. Therefore the heating system within the buildings has not been changed and operates on fairly high temperatures due to radiators used as heat distributors. Hence, the supply flow temperature of the heating system reaches 60 – 80 °C.

Similar to the system in Bilbao in the system in Warsaw a heat pump is installed to utilize the solar heat stored in the STES in a more efficient way. Contrariwise to the plant in Bilbao the heat pump has especially been developed for high temperature applications. It is a special development by the University of Ulster using the innovative refrigerants R245fa and thus achieves a thermal power of about 90 kW_{th} for maximum temperatures of about 75 °C at the condenser. The simplified hydraulic schematic of the system in Warsaw including measurement data from 24.03.2015 is shown in Figure 2.

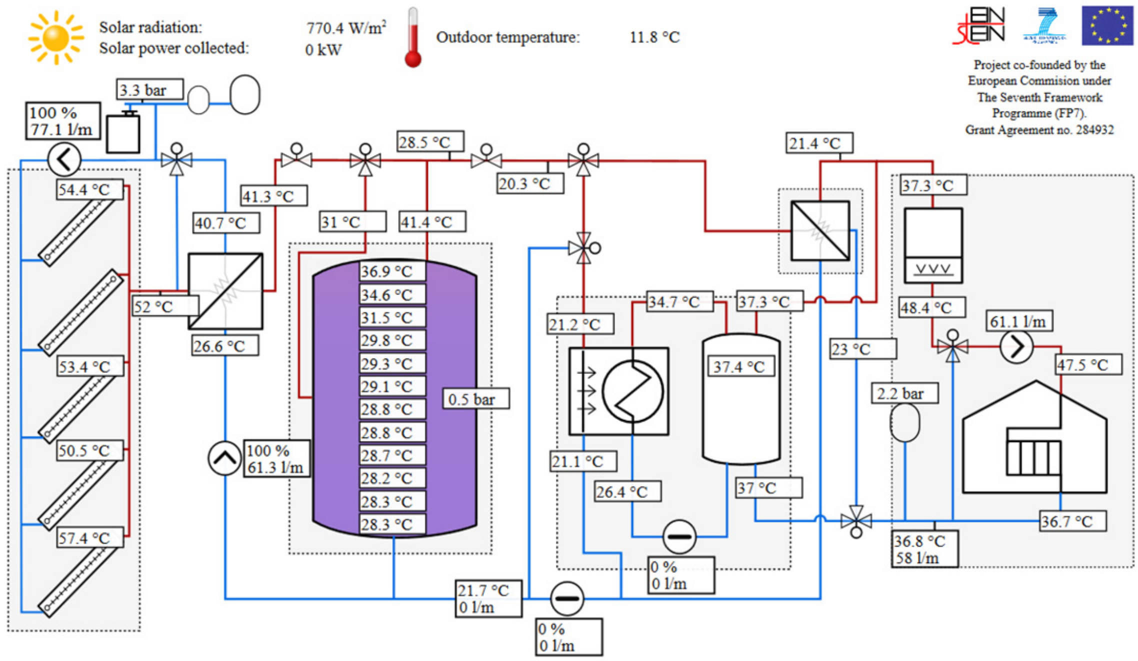

Fig. 2. Simplified hydraulic schematic of the demonstration plant in Warsaw, Poland with measurement data from 24.03.2015 (source: online monitoring layout by CIM-mes Projekt Sp. z o.o.)

4. German system in Crailsheim

The German system is going to deliver heat for space heating and hot water preparation to 43 dwellings in 3 apartment blocks. Construction work is planned to be finished by end of 2016. Fig. 3 shows an architectural drawing of the building complex.

Fig. 3. Building complex in Crailsheim, Germany; source: Fessel Architekt GmbH

4.1. Hydraulic concept

About 320 m² of solar collectors delivering heat to a hot water store will be installed on the roofs of the building complex. The hot water store is the central component of the heat supply systems where all system circuits meet. A heat pump cascade consisting of a high and a low temperature heat pump will use the store as heat source and heat sink: the high temperature heat pump provides heat for domestic hot water preparation using water at a medium temperature level of about 40 °C from the middle part of the hot water store or heat from the condenser of the low temperature heat pump as heat source. The condenser of the high temperature heat pump is connected to the upper part of the store. The low temperature heat pump provides heat at about 40 °C for space heating to the middle part of the store. The evaporator of this heat pump is connected to the bottom of the store which itself is connected to a field of helical ground heat exchangers. Surplus heat from the solar collectors which cannot be stored in the hot water store is used to heat up the ground.

The district heating is optimized with regard to installation costs, distribution heat losses and system efficiency. It is designed as a 3-pipe system using two pipes for different supply flow temperatures and one pipe for the return flow. For domestic hot water preparation, hot water is drawn from the upper part of the store to heat up domestic hot water in external fresh water stations in each apartment. The supply flow of the space heating circuit is connected to the middle part of the store. More detailed information on the heating system is given in a separate contribution to this conference [3].

The simplified hydraulic schematic of the system in Crailsheim is shown in Figure 4.

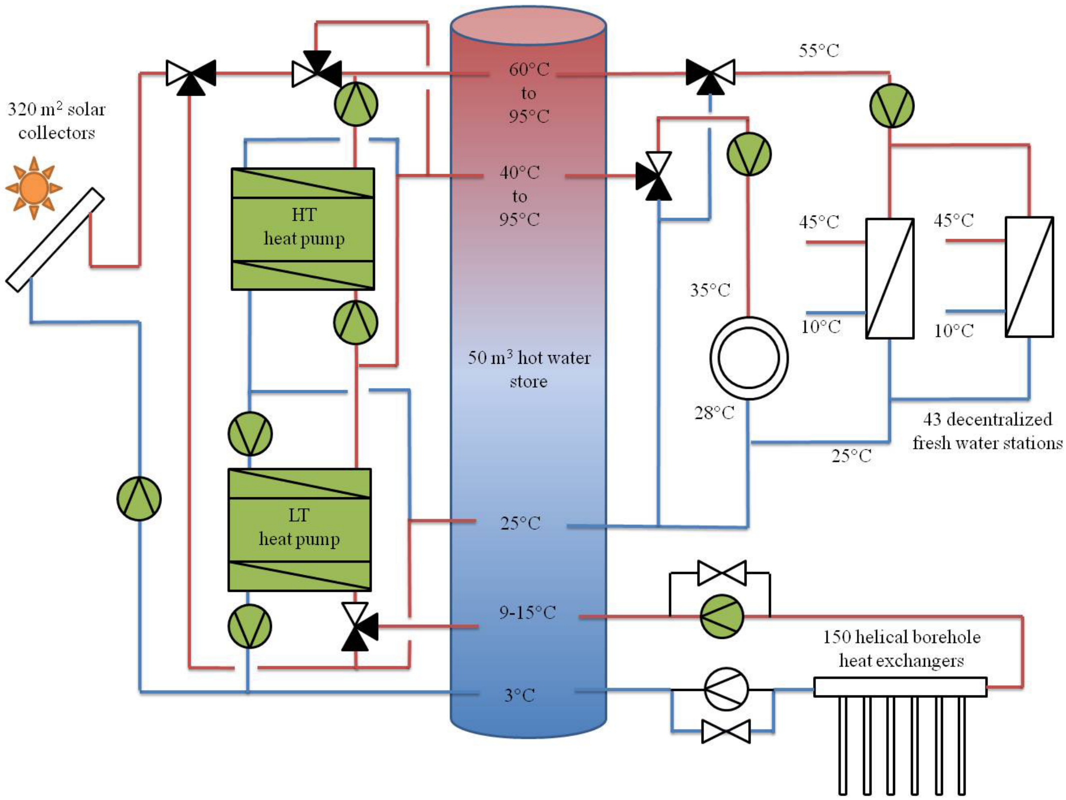

Fig. 4. Simplified hydraulic schematic of the pilot plant in Crailsheim, Germany (source: Stadtwerke Crailsheim, modified)

5. Seasonal thermal energy stores

The Spanish and the Polish system use an over ground, unpressurized hot water tank as thermal energy store with 183 m^3 and 800 m^3, respectively. Both systems have electrically driven compression heat pumps to discharge the store and a gas boiler installed for back-up heating. The German system will be monoenergetic concerning the back-up heating system. It is planned to use only electricity to drive the ground coupled heat pump cascade as a complement to the solar thermal energy with the aim to achieve a high fraction of renewable energy of around 90 %. For seasonal heat storage a combination of a 50 m^3 vacuum-insulated, pressurized, over ground hot water store and an underground thermal energy store consisting of 150 helical borehole heat exchangers installed in shallow depth will be used. Figure 5 shows the three hot water tanks being part of the systems presented.

Fig. 5. Over ground hot water store for seasonal thermal energy storage in (A) Spain, (B) Poland and (C) Germany; sources: (A) Acciona Infraestructuras S.A, (B) Mostostal Warszawa S.A. and (C), ITW, Stuttgart University

6. Results

The systems in Poland and Spain are monitored in detail since the start of their operation in summer 2014. The monitoring results show a fundamental suitability of the solar thermal heating concepts with seasonal thermal energy store to reach efficiency targets despite of moderate installation costs. In the following some selected monitoring results are shown.

Detailed planning documents and results of transient simulations for system dimensioning of the German system are also available. In contrast to both other systems for the German system a very high solar fraction as a result of a high-tech strategy is pursued.

6.1. Spanish system in Bilbao – performance of solar collectors

In the plant in Bilbao the solar collectors are installed on top of the roof of the building. In total there are three arrays of each nine solar collectors installed. They sum up to an aperture area of 62 m². The solar collectors are facing south with a slope angle of 45°. Hydraulically they operate either on the STES or on the heating system whereas intermediate operation modes are technically also possible. The solar collector type is a flat plate collector of the manufacturer Viessmann (Vitosol 200-F SV2).

In the first year of operation (August 2014 to July 2015) the annual specific yields of the collectors are 529 kWh/(m²a). This corresponds to a collector utilization ratio of 45.6 %. In Figure 6 the Input-Output diagram for the solar collector field is shown. The output heat is measured at the heat exchanger of the solar loop on the primary side. Daily values are given. In order to evaluate the performance the theoretical efficiencies are also included into the graph. It can be seen that the operation of the collectors is in a range between 30 and 70 % depending on the solar irradiation but also on other boundary conditions e.g. ambient air temperature or operational temperature of the collector.

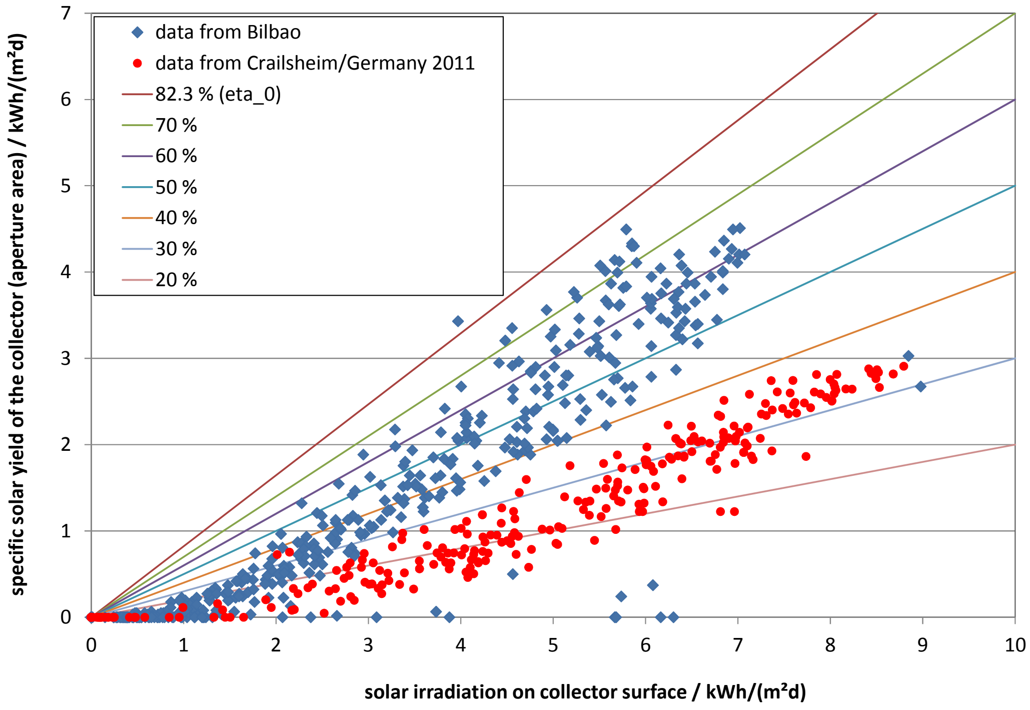

Fig. 6. Input-Output diagram for the solar collector field of the plant in Bilbao and the solar district heating system Hirtenwiesen in Crailsheim/Germany

In order to compare the results obtained from the solar collectors in Bilbao the Input-Output values are compared to results attained from Germany's largest solar district heating plant Hirtenwiesen in Crailsheim (not the one described in section 4 of this paper). This comparison is also shown in Figure 6. As it is obvious the efficiency of the solar collector field is much higher in Bilbao than in Crailsheim. In both data the losses of the solar loop are included. The reasons for the better performance of the solar collector field in Bilbao are manifold. The solar collectors applied in Bilbao have a slightly better performance curve than the ones in Crailsheim and due to the compact size of the installation in Bilbao the relative heat losses of the solar loop are smaller. In addition, the climatic boundary conditions are better in Bilbao than in Crailsheim as it is in general warmer. Furthermore the orientation is not identical. These factors make a difference but do not explain the significant difference in performance. Moreover the state of installation must be considered. In Bilbao the solar collectors are installed on top of the roof of the building. The roof is shaped slightly convex and consists of light colored metal sheets. This material can reflect some radiation from the roof in direction of the solar collectors which increases their solar yield.

6.2. Polish system in Warsaw – performance of STES

Like the STES in Bilbao the STES in Warsaw is built as an over ground tank store with a cylindrical shape. It is constructed of prefabricated metal sheets. The storage volume is 800 m³ large. Charging and discharging the store is facilitated by diffusors on three different heights within the store. It is operated at atmospheric pressure. The bottom of the store is thermally insulated by foam glass gravel, the side wall by mineral wool and the top by PUR panels and XPS. The inner storage volume is covered by an EPDM liner to assure water tightness. Due to this liner the maximum temperature is limited to 90 °C.

Within the STES there are 12 temperature sensors installed axially. Their distance to each other is 0.55 m starting with the first sensor 0.1 m above the bottom of the store. In Figure 7 the temperature distribution is shown.

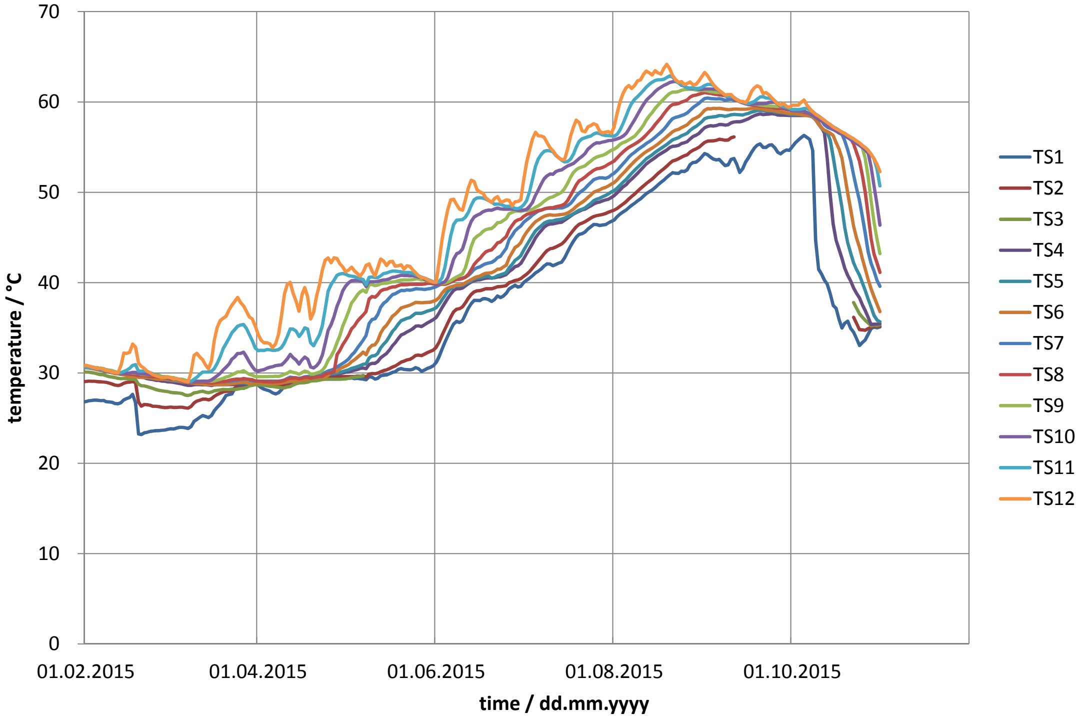

Fig. 7. Long-term temperature distribution within the STES in Warsaw

Beginning from March the solar thermal energy charged into the store increases its temperature. The maximum temperature is reached in August at the top of the store with a value of around 64 °C. On 08.10.2015 the discharging of the STES has started to use the heat to cover the building's heating demand. Hence the temperature decreases within the STES after this time. During the charging season a thermal stratification can be noticed with a maximum temperature difference of around 15 K. During the discharging season this temperature difference increases up to more than 20 K. This is a good operation as on top of the store high temperatures remain that can be used directly for heating purposes. Lower temperatures develop on the bottom of the store due to the district heating return flow temperature. Those temperatures can be used to operate the solar thermal collectors on relatively low mean temperatures. Consequently their efficiency is increased.

6.3. German system in Crailsheim

For the German system in Crailsheim only planning data is available so far, as the system is currently under construction. Table 1 contains the results of a TRNSYS simulation taken as basis for the detailed planning. According to the simulations, 1 kWh_{el} of electricity for the heat pumps ($W_{el,HP1}$ + $W_{el,HP2}$) is used to generate 11.82 kWh_{th} of heat for space heating (Q_{SH}) and domestic hot water (Q_{DHW}) including the additional heat that is needed due to the heat loss of the hot water store ($Q_{loss,sto}$). In this way, 92 % of the total heat demand is covered by renewable energies.

$Q_{sol,net}$ is the net value of solar yield used in the district heating. Q_{geo} is the low temperature geothermal heat provided by the helical ground heat exchangers. The seasonal performance factor of the heat pump cascade $SPF_{HP\text{-}cascade}$ is in total 4.62.

Table 1. Annual heat balance of the German system in Crailsheim, simulation results.

heat demand			renewable energies		electric energy		efficiency	
Q_{SH} [MWh_{th}]	Q_{DHW} [MWh_{th}]	$Q_{loss,sto}$ [MWh_{th}]	$Q_{sol,net}$ [MWh_{th}]	Q_{geo} [MWh_{th}]	$W_{el,HP1}$ [MWh_{el}]	$W_{el,HP2}$ [MWh_{el}]	$SPF_{HP\text{-}cascade}$ [-]	$f_{renewable}$ [-]
141.02	63.71	0.43	124.86	62.93	15.71	1.65	4.62	0.92

7. Conclusions

Small solar district heating systems with seasonal thermal energy stores can be a well-functioning alternative to large systems. The three different European approaches to reach both, technical and economical feasibility, show that there is no standard concept. Planning is always individually dependent on local conditions like temperatures of the district heating or geological conditions. However, several basic rules to reach well working systems have emerged during recent projects realized:

- Use of very well thermally insulated hot water store with operation temperatures from at least 10 °C to 90 °C for low heat losses, unlimited dis(charging) power and high useful storage capacity;
- Use of heat pumps to discharge the hot water stores to approximately 5 to 10 °C; the thermal power of the heat pump should be higher than the district heating load; the condenser outlet temperature should be as high as the district heating supply flow temperature.
- Low to very low distribution temperatures of the district heating network, if possible with two different supply temperatures of 35 °C for floor heating and 50 to 55 °C for hot water preparation in decentralized fresh water stations in order to drastically increase the heat amount that can be stored above the flow temperature.

Acknowledgements

The realization of the projects and the scientific work have been supported by the European Union (FP7-2011-NMP-ENVENERGY-ICT-EeB) and by the “Baden-Württemberg Research Program Securing a Sustainable Living Environment” (BWPLUS) by the Project Management Agency Karlsruhe at the Karlsruhe Institute of Technology with funds of the State of Baden-Württemberg. The authors gratefully acknowledge this support and carry the full responsibility for the content of the paper.

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